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Long Term Volumetric Evolution of an Exploited Sandbank. Case Study on the Coastal Belgian North Sea Kwintebank

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ABSTRACT

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Exploitation of aggregates from sandbanks off the Belgian coast has been growing over the two last decades. The authorities are now clearly facing the question of the sustainability of that activity. Ten to fifteen years of bathymetric measurements along reference tracks are available today. From those data, time series of volumes above a given reference level are computed and submitted to trend analysis techniques. The analysis indicates that the volume is decreasing (with a high level of confidence) almost everywhere. Estimated volume decrease is then compared to available exploitation data. Despite all the shortcomings of the procedure, the two quantities appear to be close to each others. Exploitation seems however not being the single component of the observed decrease.

ADDITIONAL INDEX WORDS: *Aggregate extraction, data processing, sand banks, bathymetry.*

INTRODUCTION

The Kwintebank (Figure 1) is one of the Flemish banks. These banks are tidal current ridges off the North Sea Belgian coast and oriented at a SW-NE direction.

The length of the Kwintebank is close to 15 km and its width is varying from 2 km in the southwestern part to 1 km in its north-eastern part. The minimum depth of water on the bank is about 5 m and can be found in the southern part also characterized by smoother profiles. Sand dunes of maximum amplitude about 6 m are found in the northern part of the bank that is characterized by minimum depth of about 8 m. Smallest sand dunes (2.5 m) are also present in the middle part of the bank. Swales of a depth of about 20m surround the bank and an asymmetrical cross-section characterizes the bank with a steepest N-W slope. A slope of 3° is not uncommon along the north-western side of the bank. The Kwintebank is inside a zone opened to sand extraction.

Registered offshore exploitation of sand on the Belgian continental shelf started in 1979. Sand extraction has grown over the past few years, raising the question of the sustainability of the exploitation. The extraction figure stays under 1.000.000 m^3 $year^{-1}$ until 1990. Afterwards, a constant increase is observed during the 10 following years resulting in figures approaching 2.000.000 m^3 $year^{-1}$ today.

From the early 80's, just after the registered exploitation started, a monitoring program was set up. The followed methodology included bathymetric measurements along transect lines perpendicular to the main axis of the Kwintebank (see Figure 1). In our area of interest, the amplitude of the tide (mean value) is close to 2 m. All (time varying) depth measurements need therefore to be referenced to a unique vertical level. For navigational charts, that vertical reference level is the Mean Low Low Water Spring (MLLWS) level. In the Belgian coastal waters, the M_2 tidal reduction method developed by VAN CAUWENBERGH *et al*. (1993) is used to refer all depth soundings to that level. A heave compensator is also coupled to the echo sounder. Volume of a given section above a specified reference level is computed from the corrected bathymetric information. Time series of these volumes are analysed for trend.

METHODS

The Data Sets

The primary data are bathymetric soundings along transects. For the sake of completeness, we have to stress that all data used within the frame of the present study were not all directly available in a digital format. Indeed, for some of the old data, the single information still available was the drawing made just after the campaign. For those profiles, an automatic digitisation technique has been used to reconstruct 'analogue' profiles. The number of profiles available for each reference line presented on Figure 1 is listed in Table 1. For each line, the distinction is made between the number of profiles directly available in a digital format and the number of profiles for which the automatic digitisation technique has been necessary. The number of usable profiles proposed at Table 1 is obtained by adding the number in digital and analogue classes and subtracting the number of duplicates. When duplicates occur, the digital profile is preferred. Duplicates have also been used for the verification of the automatic digitisation procedure.

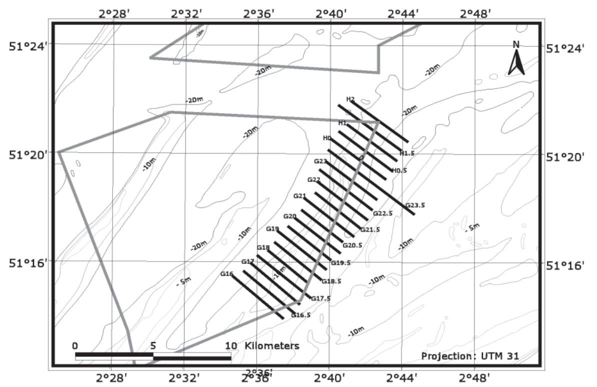

Figure 1. The Kwintebank zone: the gray lines show the limits of the zone opened to sand extraction. The black solid lines correspond to the *pre-defined* tracks of the monitoring program.

Table 1. *The 1st column gives the code of the track (see Figure 1). The 2nd column indicates the year of the first measurement. The 3rd and 4th columns give the number of available profiles in analogue and numerical format, respectively. The following columns give the maximum number of usable profiles, including the badly navigated ones and the outliers.*

n°	first prof.	analogue	digital	usable	Bad Nav	Outliers
G16	88	23	25	41	5	3
G16.5	92	8	11	15	2	1
G17	88	26	31	42	5	3
G17.5	90	14	13	22	3	1
G18	88	39	27	44	7	5
G18.5	90	12	13	19	3	1
G19	87	42	23	57	7	5
G19.5	90	12	14	20	5	2
G20	88	43	26	52	7	6
G20.5	90	13	13	18	4	2
G21	88	25	26	44	5	2
G21.5	89	16	12	22	4	0
G22	88	42	28	52	7	1
G22.5	89	16	13	25	2	2
G23	92	0	27	16	10	1
G23.5	94	0	14	11	3	0
H00	88	50	29	54	9	4
H00.5	89	15	16	21	5	0
H01	88	47	28	55	7	5
H01.5	91	6	14	12	5	3
H02	90	20	27	21	1	3
Total		469	430	663	106	50

The Error Budget

The error budget characterising the data taken with the research vessel *Belgica* as published in NORRO *et al.* (2003) is presented here. Distinction is made in this table between three different sources of errors: error in recording, error in reduction procedures and error in navigation. Discussion of all components can be found in SUMARE deliverable D1 (2001) and NORRO *et al.* (2002). In the next section, the focus will be on the evolution in time of the volume above a reference depth (-15 m) of each transect. All errors listed in Table 2 do not contribute in the same way to the uncertainty on the computed volume. Indeed, some of these errors are varying independently from one sounding to another while others should be considered as being almost constant at the scale of the sailing of a single transect. Enter this second category: the error on the calibration of the echo sounder that is made at the time start of each survey, the error affecting the tidal reduction, the error in static draught and the error in the variation of that static draught.

It can be noted that the total error figure obtained at Table 2 fits inside the International Hydrographic Organisation standard at the order 1 (IHO Standards for Hydrographic Surveys, 1988).

Another distinction is made between the data collected before 1993 and those collected afterwards. That distinction emphasizes the influence of the introduction of the heave compensator and that of a updated version of the tidal reduction method.

The Ouliers

A common feature when working with data is the occurrence of 'bad data point' or outliers. In this case, two causes of outlying are envisaged:

- Profiles that are badly navigated
- Profiles that have bad vertical registration or too short to cover completely the reference line

The fifty-seven available profiles for the reference line G19 are presented on figure 2. It appears clearly that some of these profiles are badly vertically aligned. Similar problems have been encountered for each reference line. It makes no doubt that a bad vertical alignment has a strong impact on the computed volume above a reference depth. The influence of these outliers

Table 2. *Error budget for the data taken with the single beam sensor on board of the Research Vessel Belgica. Error bounds are assumed to be at the ±2σ level. For those terms influenced (slightly) by the water depth (e.g., the echosounder, the speed of sound, the presence of slopes), the given value is for a mean water depth equal to 20 (From NORRO et al. 2003).*

Source of error	**Precision data 1988-1993**	**Precision data After 1993**
	Error in recording	
Echosounder	+4.0 cm/-4.0 cm	+4.0 cm/-4.0 cm
Speed of sound	+2.5 cm/-2.5 cm	+2.5 cm/-2.5 cm
Heave	+10.0 cm/-10.0 cm	+2.5 cm/-2.5 cm
Presence of slopes	-3.0 cm	-3.0 cm
Subtotal	+10.0 cm/-13.0cm	+4.0 cm/-7.0 cm
	Error in reduction procedures	
Tidal reduction	+32.0 cm/-32.0 cm	+13 cm/-13 cm
Static draught	+5.0 cm/-5.0 cm	+5.0 cm/-5.0 cm
Var. in stat. draugh t	+5.0 cm/-5.0 cm	+5.0 cm/-5.0 cm
Subtotal	+33.0 cm/-33.0 cm	+15.0 cm/-15.0 cm
	Error in navigation	
Error in navigation	+8.5 cm/-8.5 cm	+8.5 cm/-8.5 cm
Total error	***+34.0 cm/-37.0 cm***	***+16,4.0 cm/-19,4 cm***

on the trend analysis of the time series is discussed in the next section.

The quality of navigation appeals furthers comments. Recall that the data used are a mixture of data initially available either on paper (a plot of the depth profile) or in a digital format (a data set with all the [x,y,z,t] relevant information). The depth measured at the position of the ship is always taken as being the depth at the nearest point of the theoretical track. This is the procedure followed to draw depth profiles like these presented in figure 2. For the profiles available in digital format, it is easy to compute the distance with respect to the theoretical track. The results for the 23 profiles along the reference line G19 are presented on figure 3. Note that the distance is positive when the ship is on the left of the track and negative when it is on the right of the track.Clearly, navigated tracks rarely follow exactly theoretical tracks due to vessel handling possibilities in response to weather conditions. The impact of these errors in navigation (not accounted for in table 2) on the volume above a reference depth is difficult to assess *a priori*. In the area of G19, where the shape of the bank is rather smooth, we expect a relatively small impact (this will be confirmed later, see figure 4). In the north-eastern area of the bank, the impact could be larger notably due to the presence of sand dunes.

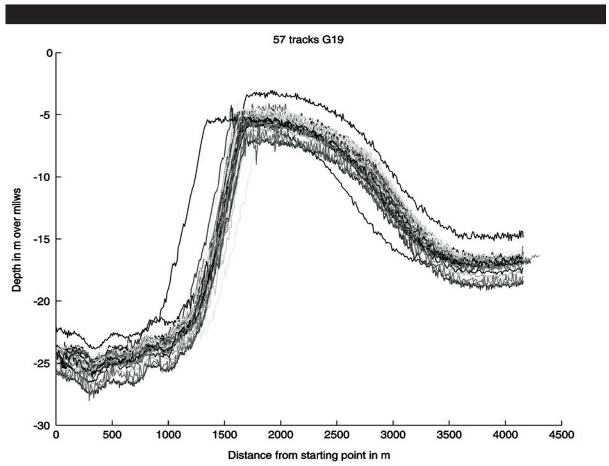

Figure 2. The fifty seven profiles available for the reference line G19

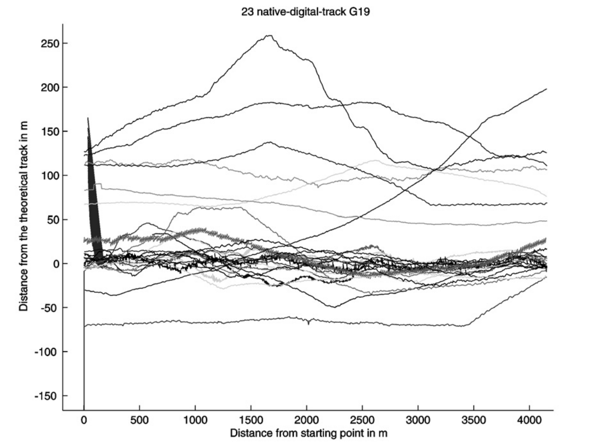

Figure 3. Distance with respect to the ideal track for 23 native digital navigated tracks on G19 reference line.

For morphological studies, DE MOOR (2002) asserts that a distance with respect to the ideal track greater than +/- 20 m is sufficient to consider that the data should not be taken into account. To determine the number of “badly navigated” tracks given in Table 2, that constraint has been slytly relaxed to +/- 50 m.

As the quality of the navigation can only be checked for profiles available in the digital form, this introduces a discrepancy in the quality control of the whole data set.

Multibeam Data

From 1999, multibeam echo sounder is in use onboard *R/V Belgica*.

That new generation of instrument incorporating numerous sensors is able to take bathymetric measurements in a band characterised by a strip depending among other of the water depth. The result is that a complete coverage of a given surface such as a sandbank is now possible. For the Kwintebank, such map exists and is processed by the Fund for sand extraction of the Belgian Ministry for Economic Affairs. The data used to compute the Digital terrain Model (DTM) have been taken in November 1999 for a restricted zone located in the central part of the bank and, from January 2000 to March 2000 for the remaining of the central part of the bank. Northern and the southern tips of the bank have been surveyed from November 2001 to February 2002. The complete map has been thus built on data collected during a 28 months period. If the large scale stability of the bank could be assumed, it is probably not the same with the small scale features. The question of the 'synopticity' of observations covering such a period of time arises even of a significant gain in the spatial domain is recognized. One additional profile has been taken for every section presented at Figure 2 by the mean of extracting the DTM value on every point of the theoretical reference line considered. That profile is included in the number cited at Table 1.

The time series of volume above the reference depth (-15m) is presented at Figure 4. The mean volume is equal to 11895 m^3m^{-1}. The standard deviation is equal to $\sigma = 1068\ m^3m^{-1}$. A trend is perceptible. It will be discussed in the next section. The impact of a bad vertical registration on the estimated volume is clearly visible.

Parametric and Non-parametric Methods Applied to the G19 case

The first method used for trend extraction is the parametric method known as ordinary least square (OLS). Using that method, quality of the fitted model can be approached by several ways. The classically used r^2 parameter shows in this case that 12% of the variance of the data can be explained by the proposed model. If no general rules exist to define what is an r^2 too low for a useful regression equation, hypotheses testing can

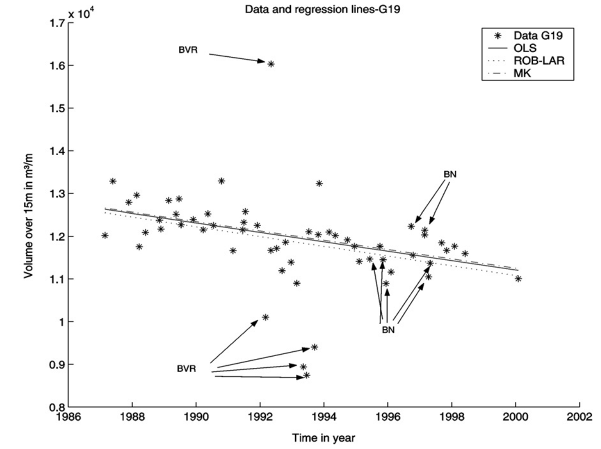

Figure 4. Section G19 volumetric evolution time series. Reference depth is -15m. BN are 'Bad Navigation' and BVR are 'Bad Vertical Registration'. OLS, ROB-LAR and MK are the different linear models fitted to the data.

be performed to characterise the significance of the slope. Nevertheless these calculations are based on the normality of the model residuals.

Figure 5 showed that few data points (8) depart from the normality invalidating hypotheses testing on the parameters of the model. The analysis of the temporal evolution of the residuals (not shown here) indicates that a first order polynomial is suitable for the problem. No trend can be detected and the distribution is almost homoscedastic.

Two options are available in order to cope with outliers. The first option is to remove outliers but they have to represent 'true' bad data point. The second one is to consider nonparametric methods such as robust regression schemes. Such methods permit to reduce the influence of outliers on the fit and remain usable even if the normality of the residual is not encountered. The Mann-Kendall (MK) rank-based method and the robust least absolute residuals regression (ROB-LAR) method minimizing the absolute difference of residuals instead of the squared differences are used as nonparametric methods in this paper. Figure 4 illustrates the three fits of the complete data set for G19 (57 data points).

After the examination of the residuals, it is possible to have more 'quality indexes' of the fit. They can be expressed in term of significance where applicable. Table 3 presents theses parameters for the three proposed methods used in this case. The table also presents results when the 5 outliers have been manually removed. If hypothesis testing is not valid for the OLS case with 57 data points, the two robust methods show a highly significant negative slope.

It can be concluded from this analysis that when outliers are removed, both methods (OLS and MK) give similar results but

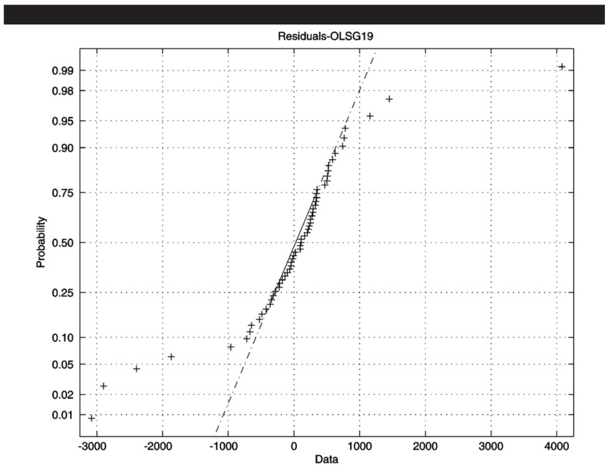

Figure 5. Probability plot of the OLS model residual for the volume time series G19.

Table 3. *Quality of the fits presented at Figure 4. r^2 is the square of the correlation coefficient, Tau the correlation coefficient for the MK scheme, ρ the slope of the fitted linear model expressed in $m^3\ m^{-1}\ y^{-1}$ and α(ρ) the related significance parameter. The last two columns concern tests made after removing the 5 potential outliers.*

Fit	r^2	tau	ρ	α(ρ)	ρ (52 pts)	α(ρ)(52pts)
OLS	0.12	-	-114.3	n/l	-105.6	<0.001
MK	-	-0.38	-109	<0.001	-106.7	<0.001
ROB-LAR	0.73	-	-110.2	<0.001	-	-

when outliers are present, only nonparametric should be used. The advantage of using robust fits such as Mann-Kendall method is the independence toward making hypothesis on outliers. This also permits a uniform treatment of the datasets. Mann-Kendall method will be used for the analysis of the complete datasets.

Analysis of the Complete Dataset with the Mann Kendall Non-parametric Method

All reference lines time series have been analysed in the same way as G19 time series with the Mann-Kendall robust method. Results are presented at Table 4.

The analysis presented here proposes a significant decrease in volume of all except three sections of the Kwintebank. Section G16, G16.5 and G23 are characterised by a clear non-significant regression.

Table 4 situates the most important decrease in quantity at the level of the reference line G21 while the smallest one is found for reference line H02, but these two reference lines are characterised by very different volumes over 15m.

As a conclusion, it can be computed an overall figure for volumetric evolution of the Kwintebank that is a decrease in volume above 15m (MLLWS) of 1.5% y^{-1}.

Global Comparison Between Volumetric Evolution and Extraction Data

It will be investigated how far it is possible to relate quantitatively the data on extracted volume and the volume decreases computed with the sequential profiles approach.

Exploitation of aggregate data are available in two different formats. The first one consists in the register of the quantities of aggregates that are unloaded at every shift of the various dredging vessels. That register exists from the start of the exploitation. The second source of information is the 'black box' data. The 'black box' is a memory device recording among others, position, vessel speed and pump status every half-minute. Such information is regularly retrieved and stocked in a database. The data are available from November 1996.

From the database of extracted volumes (black-box), we estimate at 762000 m^3 the amount of sand extracted on a yearly basis in the main area of interest of the present study (the Kwintebank; depth above 15 m). According to DEGRENDELE *et al* (2002), extraction figures based on data from vessels equipped with black boxes represent only 65% of the total activity. If we assumed common working practices for all vessels during the period covered by those black boxes (November '96 March 2001), the volume extracted on a yearly basis in the area should be close to 1172000 m^3. *Stricto sensu*, that value is only valid for the period covered by the data.

Now, the data from the black boxes cover only a period of approximately 4 years while profile data cover more than 10 years. Extraction has not been 2002. Evaluation constant during that period. To get, however, a first estimate of a mean extracted volume over the same period, we have assumed that the amount of extracted material in the area of interest has always represented the same fraction of the total exploited volume than that observed during the period of the black boxes. Doing that, we arrive at a mean extracted volume equal to 0.9 $10^6\ m^3 y^{-1}$. This is obviously less than before but at least the order of magnitude is the same.

Table 4: *Goodness of fit statistics and other results of the Mann-Kendall regression made for all references lines. Non-significant (95 %) cases are noted by shaded cells. Slopes are expressed in $m^3 m^{-1} y^{-1}$*

Ref	α	ρ	Mean Vol.	%
G16	0.25	-40.5	9017	-0.4
G16.5	0.9	8.7	12322	0.07
G17	0.004	-109.0	14619	-0.7
G17.5	<0.001	-167.0	14712	-1.1
G18	0.004	-109.1	14160	-0.8
G18.5	<0.001	-113.5	13850	-0.8
G19	<0.001	-109.1	11880	-0.9
G19.5	<0.001	-165.1	9603	-1.7
G20	<0.001	-131.9	8000	-1.6
G20.5	<0.001	-221.4	5586	-3.9
G21	<0.001	-241.9	4697	-5.1
G21.5	<0.001	-215.2	3221	-6.7
G22	<0.001	-71.1	2177	-3.3
G22.5	<0.001	-44.0	1516	-2.9
G23	0.83	25.7	1886	1.3
H00	<0.001	-100.3	971	-10.3
H00.5	<0.001	-58.9	516	-11.4
H01	0.004	-11.4	243	-4.5
H02	0.003	-26.0	198	-13
Global		-1901.1	129174	

The trend analysis presented earlier indicated a decrease of the order of -1.5 $10^6\ m^3 y^{-1}$. Another approach not presented here, using complete volume reconstruction (Sumare Deliverable D5A, 2003) lead to a similar value of -1.9%y^{-1}.

Our estimate of the extracted volume is below the two computed decreases. It is however not too far from the lower bound.

It seems appropriate to conclude that indeed the sand extraction has an impact on the volume of the Kwintebank. That the estimated impact is greater than the estimated workload raises the question: “Does it mean that the activity has perturbed the dynamic balance of the bank ?”. A modelling approach is under development to address that question.

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